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Canty, Morton J.; Nielsen, Allan Aasbjerg

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Site Monitoring with Synthetic Aperture Radar Satellite Imagery

Morton J. Canty[1] and Allan A. Nielsen[2]

1. Institute for Energy and Climate Research, IEK-6,
Jülich Research Center, D-52425 Jülich, Germany

2. DTU Compute, Department of Applied Mathematics and Computer Science,
Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

Abstract:

Based on a statistical test for the equality of polarimetric matrices following the complex Wishart distribution and a factorization of the test statistic, change analysis in a time series of multi-look polarimetric SAR data in variance-covariance or polarimetric matrix representation is carried out. The test statistic and its factorization detect if and when change(s) occur. This paper provides a short explanation of the method, describes available software, and gives examples of potential applications for site monitoring.

Keywords: multi-temporal SAR imagery, polarimetry, change detection, site monitoring

1. Introduction

Space-borne synthetic aperture radar (SAR) sensors with spatial resolutions of the order of 5-20 meters, revisit times of the order of weeks and complete independence from solar illumination and cloud cover offer an attractive potential source of information remote for site-monitoring. Additionally, many of these platforms collect polarimetric data, increasing their capability to discriminate surface features. Satellite platforms with these capabilities include the Japanese ALOS-2, the Canadian Radarsat-2, the Italian COSMO-Skymed, the German TerraSAR-X, and the European Sentinel-1.

A characteristic task in site monitoring under some civil, military or environmental control regime involves the automatic registration of significant changes which might involve unreported or clandestine activity or environmentally significant events. In [1] change detection in a time series of polarimetric SAR data is described involving a so-called *omnibus test statistic* (and its factorization) for the equality of polarimetric matrices following the complex Wishart distribution. The procedure is capable of determining, on a per-pixel basis, if and when a change at any prescribed significance level has occurred in a time series of SAR images. Single polarization (intensity data), dual polarization (for example vertically polarized emission, vertical and horizontal reception) and full quad polarization (all four combinations of vertical and horizontal emission/reception) can be analyzed.

Since the omnibus method can detect not only if changes occur but also, within the temporal resolution of an image sequence, when they occur, long time series of frequent acquisitions over relevant sites are of especial interest. One convenient source of such data is the Google Earth Engine (GEE) [2] which ingests Sentinel-1a and Sentinel-1b data as soon as they are made available by the European Space Agency (ESA) and provides a very convenient application programming interface (API) for accessing and processing the data.

In the Section 2 below we provide a brief, qualitative description of the omnibus method. In Section 3 the available software tools are outlined and in Section 4 some examples involving Sentinel-1 data are presented. The paper concludes in Section 5 with an outlook to future developments and possibilities.

2. The omnibus method

The term "multi-look" in SAR imagery refers to the number of independent observations of a surface pixel area that have been averaged in order to reduce the effect of *speckle*, a noise-like consequence of the coherent nature of the radar signal emitted from the sensor. The observed signals are multivariate complex Gaussian distributed and their variance-covariance representations, when multiplied by the number of looks, are correspondingly complex Wishart distributed. This distribution is the multivariate complex analogue of the well-known chi-square distribution for the variance of Gaussian-distributed scalar observations.

The complex Wishart distribution is completely determined by a singe parameter Σ, the covariance matrix. Given two observations of the same area at different times, one can set up a so-called *hypothesis test* in order to decide whether or not a change has occurred between the two acquisitions. The *null hypothesis* is that $\Sigma_1 = \Sigma_2$, i.e., the two observations were sampled from the same distribution and no change has occurred, and the *alternative hypothesis* is $\Sigma_1 \neq \Sigma_2$, in other words, there was a change. Since the distributions are known, a *likelihood ratio test* can be formulated which allows one to decide to a desired degree of significance whether or not to reject the null hypothesis. Acceptance or rejection is based on the so-called p-value, which in turn may be derived from the (approximately known) distribution of the likelihood ratio test statistic. In the case of $k > 2$ observations this procedure can be generalized to test a null hypothesis that all of the k pixels are characterized by the same Σ, against the alternative that at least one of the Σ_i , I = 1...k, are different, i.e., that at least one change has taken place. Furthermore the omnibus test procedure can be factored into a sequence of tests involving hypotheses of the form:

$\Sigma_1 = \Sigma_2$ against $\Sigma_1 \neq \Sigma_2$
$\Sigma_1 = \Sigma_2 = \Sigma_3$ against $\Sigma_1 = \Sigma_2 \neq \Sigma_3$
and so forth. The tests are statistically independent under the null hypothesis. In the event of rejection of the null hypothesis at some point in the test sequence, the procedure is restarted from that point, so that multiple changes within the time series can be identified.

3. Software

The authors provide access to Matlab [2] and Python [3] code which is suitable for the analysis of multi-temporal polarimetric SAR imagery with the sequential omnibus algorithm. Data from any of the aforementioned platforms can be processed. For users with access to the Google Earth Engine [4] a web-based application is also available [5] with which long time series of Sentinel-1 images can be accessed from a browser. The data can either be downloaded for processing off-line with the Matlab or Python code, or evaluated directly on the Google servers. In the latter case the algorithm is programmed with the Earth Engine Python API.

3. Examples

The following examples are based exclusively on Sentinel-1 images obtained from the GEE database. The data, acquired in instrument Interferometric Wide Swath (IW) mode, are S1 Ground Range Detected (GRD) scenes, processed using the Sentinel-1 Toolbox [6] to generate a calibrated, ortho-corrected product. This processing includes thermal noise removal, radiometric calibration, and terrain correction using Shuttle Radar Topography Mission 30 m (SRTM 30) data. The change detection analyses were performed on-line with the GEE Python API on time series of 5-look, dual polarimetry diagonal only (VV, VH) images with a spatial resolution of 20m. The GEE software described in [5] allows the user to search anywhere on the globe for time series of Sentinel-1 SAR images, clipping the data to the time period and spatial region of interest, the desired viewing angle (relative orbit number, ascending or descending node) and polarization (dual or single).

Figures 1 and 2 show a change frequency map derived from a 24-image time series over the NATO air base at Geilenkirchen, Germany. The frequent movements of aircraft (in this case often AWACS training machines) to and from their parking positions are clearly evident.

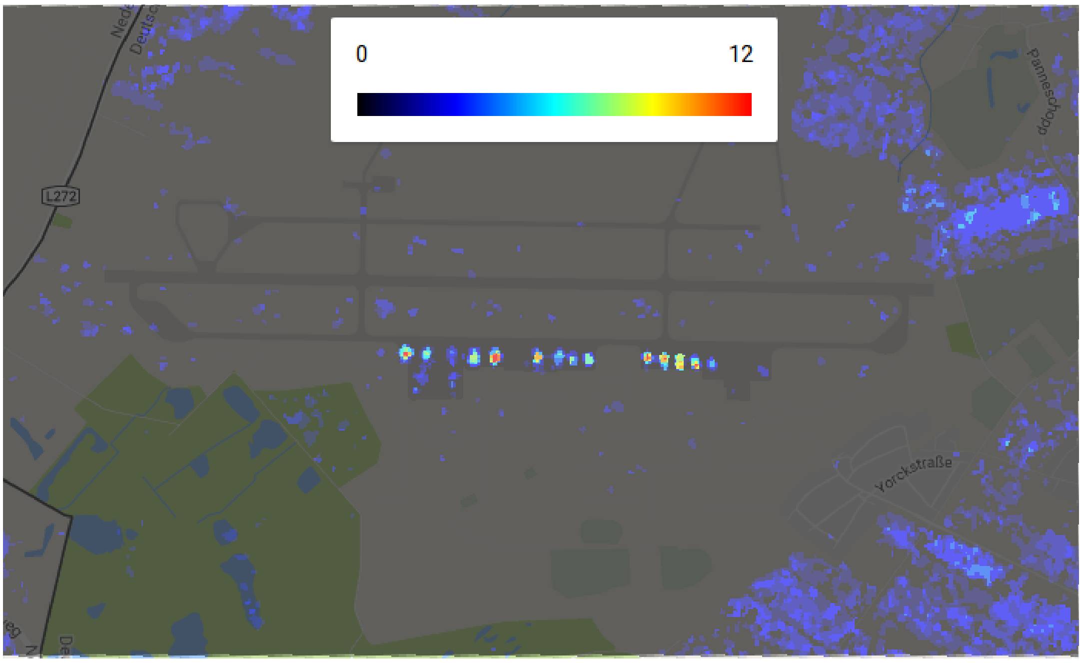

Figure 1. Change frequency map over the NATO Airbase at Geilenkirchen, Germany. The data were derived from a time series of 24 Sentinel-1 acquisitions, beginning Feb. 3, 2016, ending Oct. 10, 2016. The map is overlain onto a Google Maps background.

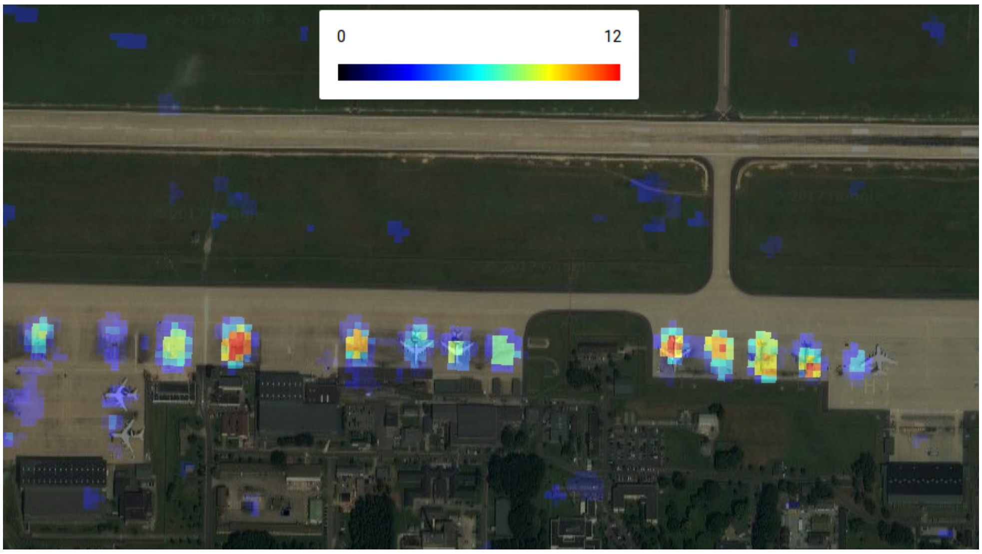

Figure 2. Frequency map as in Figure 1, now overlain onto a Google Earth background.

Figure 3 shows an example of flood monitoring, tracing the dangerous filling of the Oroville, California reservoir in late 2016, early 2017, which threatened to burst the retaining dam.

Figures 4 and 5 show two seaports on the Libyan coast, Tripolis and Benghazi, respectively. In the former one sees considerable shipping activity, whereas in the latter none at all.

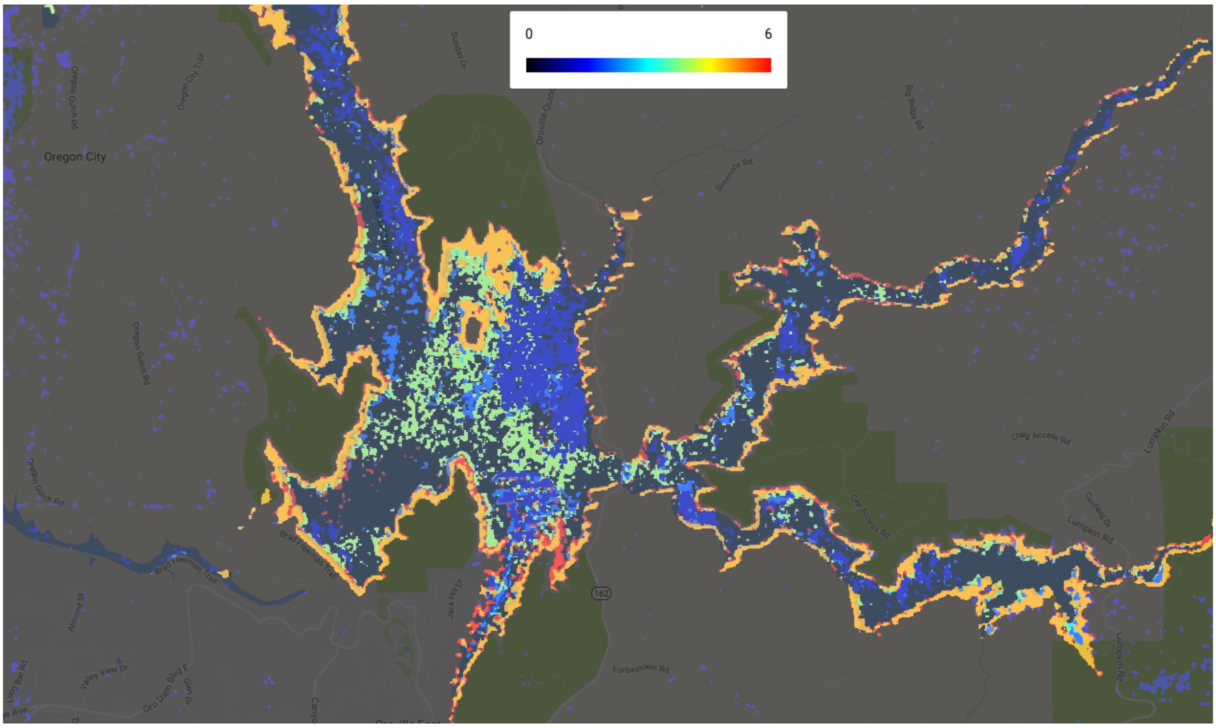

Figure 3. Change map showing the time of the first significant change in the Oroville, California reservoir over a time sequence of seven Sentinel-1 images beginning March 14, 2016 and ending Jan. 26, 2017: blue indicates change in the first, red in the last (sixth) interval.

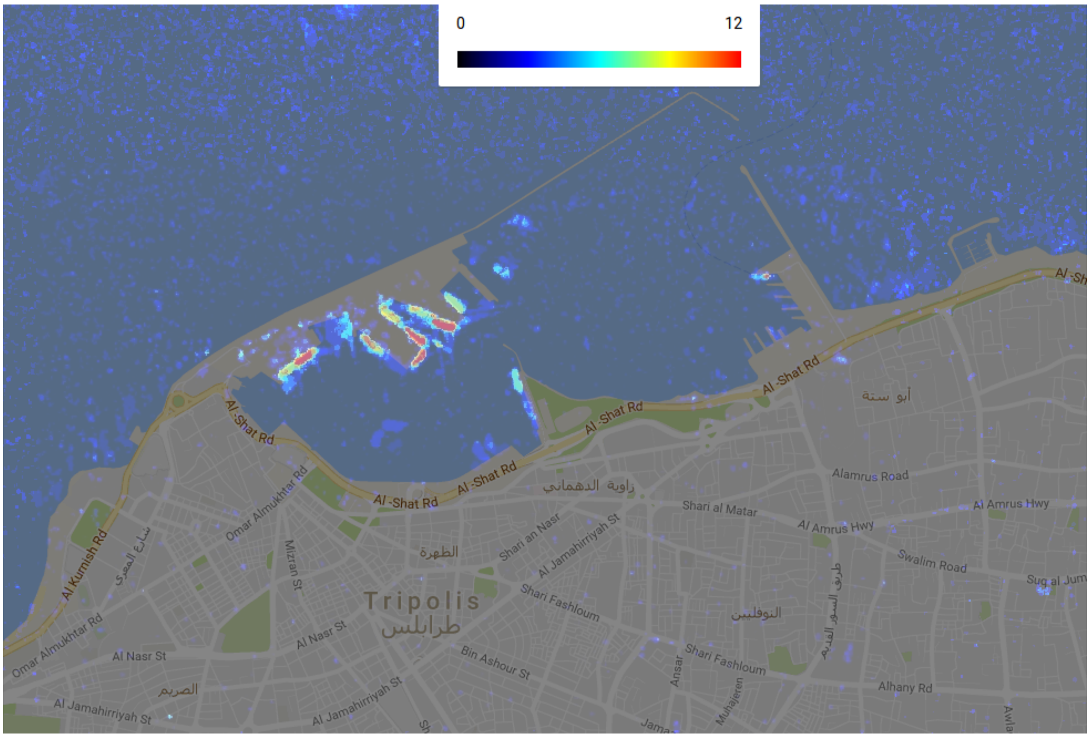

Figure 4. Change frequency map of the port of Tripolis, Libya. Time series of 28 images beginning Feb. 2, 2016 and ending Nov. 30, 2016.

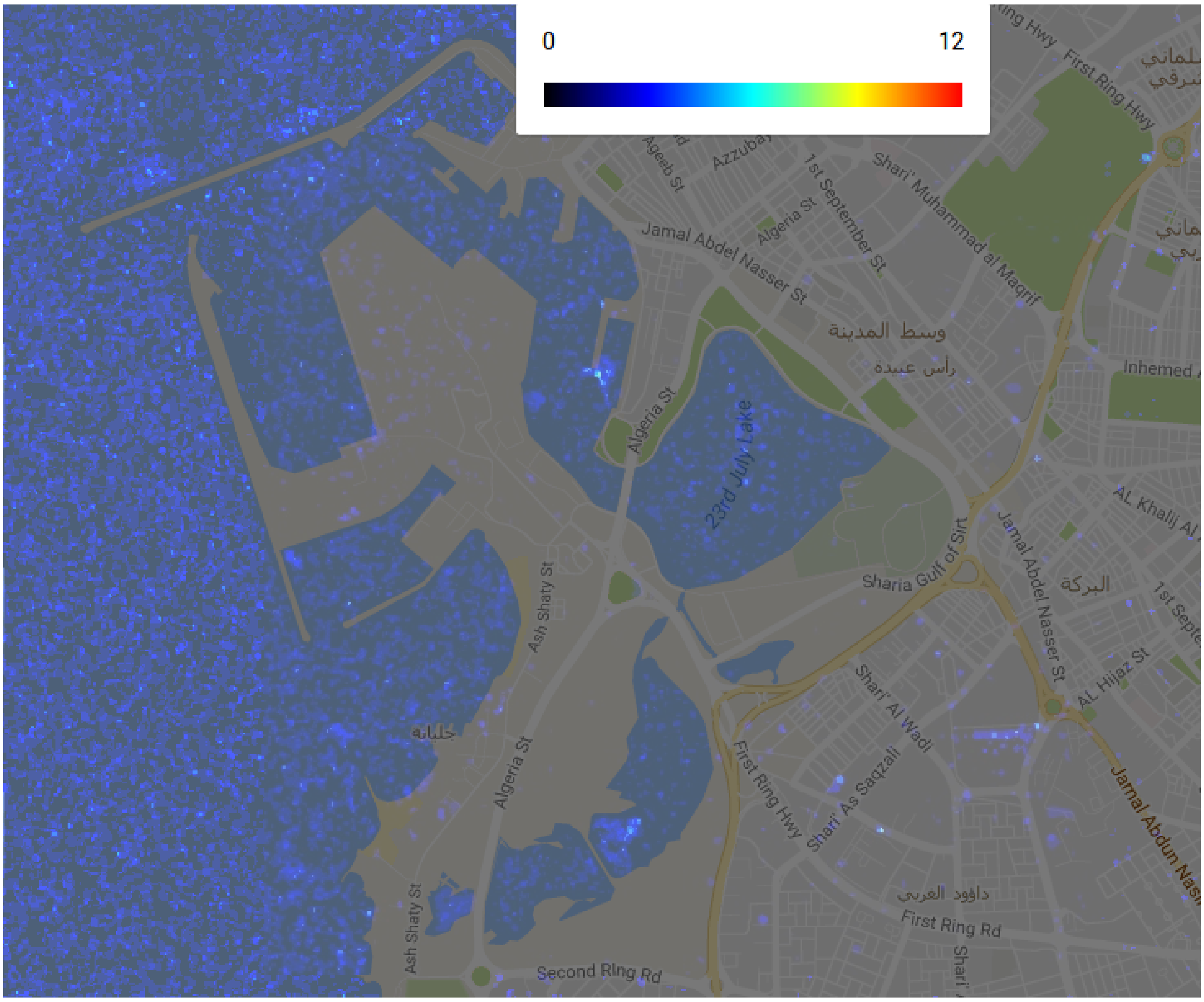

Figure 5. Change frequency map for the port of Benghazi for the same time period as Figure 4.

4. Conclusion

While the GEE platform has obvious advantages for historical or on-going site monitoring, there are currently some disadvantages: First, the complex off-diagonal elements of the polarimetric matrix are not available, implying some loss in discrimination. Second, the stored pixel values in the GEE database are clamped to the first and 99th percentile to preserve the dynamic range against anomalous outliers, and quantized to 16 bits. The resulting saturation of the brightest pixels tends to be concentrated in built-up areas or to be associated with other man-made objects, further reducing sensitivity. Finally, the ground resolution of 20m restricts the applicability of site monitoring to detection of correspondingly large changes. The examples chosen reflect this restriction in particular.

Nevertheless, we have demonstrated, making use a sound, statistically-based algorithm, that change detection for site monitoring with archived SAR data is both feasible and convenient.

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